New Tasks in Beam-Beam Modeling

N. Malitsky, N. D'Imperio,

C. Montag, R.Tomas

High Performance Computing with BlueGene/L and QCDOC
Brookhaven National Laboratory
October 27-28, 2004

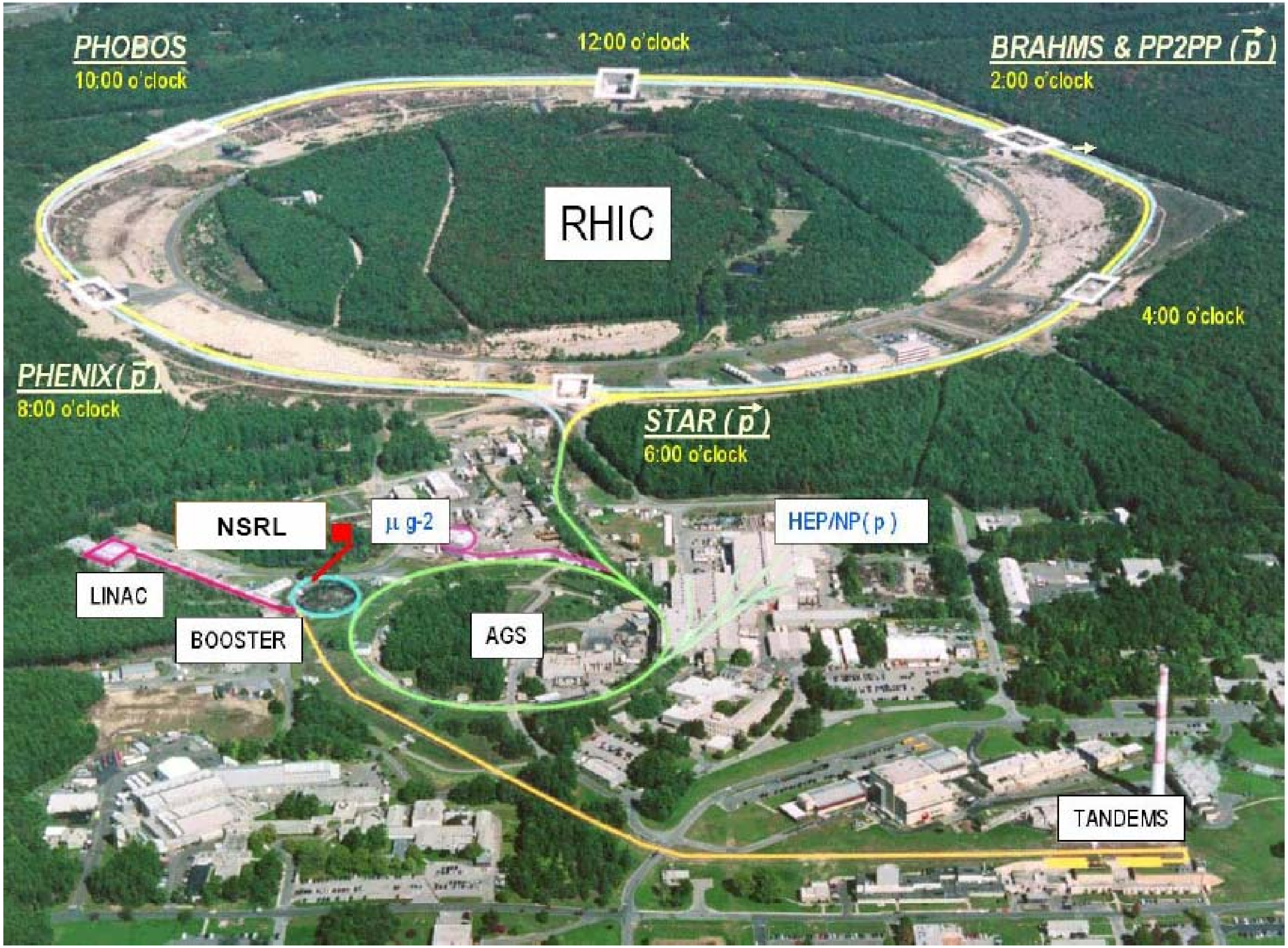
Acknowledgements

- **C-A Department:** M. Bai, I.Ben-Zvi, M.Blaskiewicz, A.Fedotov, W. Fischer, V.Litvinenko, A.Luccio, F. Pilat, V.Ptitsyn, T. Roser, T. Satogata, J. Wei
- **Computational Science Center:** J. Davenport
- **IT Division:** M. Cuttler
- **Cornell University:** R.Talman
- **IBM:** G. Bhanot, B. Walkup

Outline

- **BNL C-A Complex**
  - **RHIC**
  - **RHIC II**
  - **eRHIC**
- **Beam-Beam Application**
  - **Conceptual Model**
  - **UAL-based Solution**
- **Benchmark**
- **Summary**

C-AD Accelerator Complex



Future plans for RHIC

T. Roser. Beam Experiments workshop, September 16, 2004

Machine goals for next 4 years (pre-RHICII):

- **Enhanced RHIC luminosity (112 bunches, $\beta^* = 1$m):**
- **Au – Au: 8×10^{26} cm^{-2} s^{-1} (100 GeV/nucleon)**

4× design
2× achieved

- **For protons also 2×10^{11} protons/bunch (no IBS):**
- **p↑ – p↑: 60×10^{30} cm^{-2} s^{-1}; 70 % polarization (100 GeV)**
  150×10^{30} cm^{-2} s^{-1}; 70 % polarization (250 GeV)

  (luminosity averaged over store delivered to 2 IRs)

16× design
6× achieved

- **Review by Machine Advisory Committee, Nov 8-9, 2004**

EBIS received CD0 this summer; interest in Uranium beams for RHIC

RHIC II (e-cooling, 40 × design)

eRHIC

P-P Luminosity limit: beam-beam effect

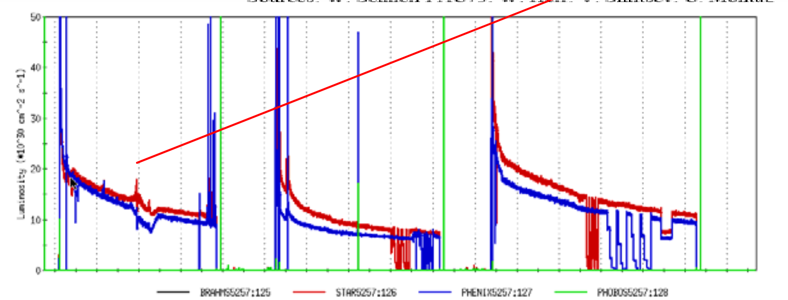
W. Fischer. RHIC Retreat, June 7, 2004

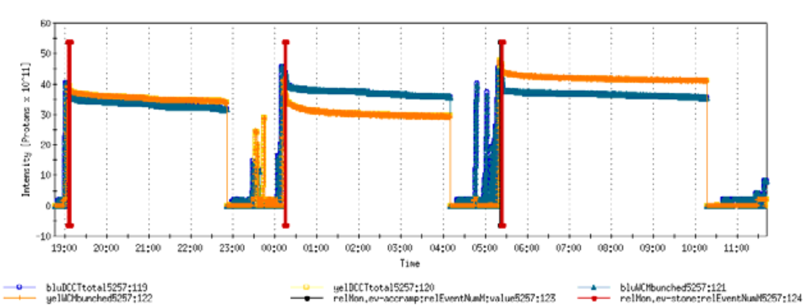
	ISR	SPS	Tevatron Run I	HERAp	RHIC* pp 2003	RHIC pp goal	LHC
Bunches per beam	coasting	3	6	174	55	111	2808
Experiments	6	2	2	2	4	2	4
Parasitic interactions		4	10	—	—	—	120
beam-beam ξ / IP	0.001	0.009	0.008	0.0007	0.004	0.007	0.003
Total bb tune spread, max	0.008	0.028	0.024	0.0014	0.015	0.015	0.010

* Numbers for ε_N=15µm and N_b=0.7 10^{11}

Sources: W. Schnell PAC75, W. Herr, V. Shiltsev, C. Montag

So far, there is no comprehensive model explaining the beam-beam tune spread criteria.



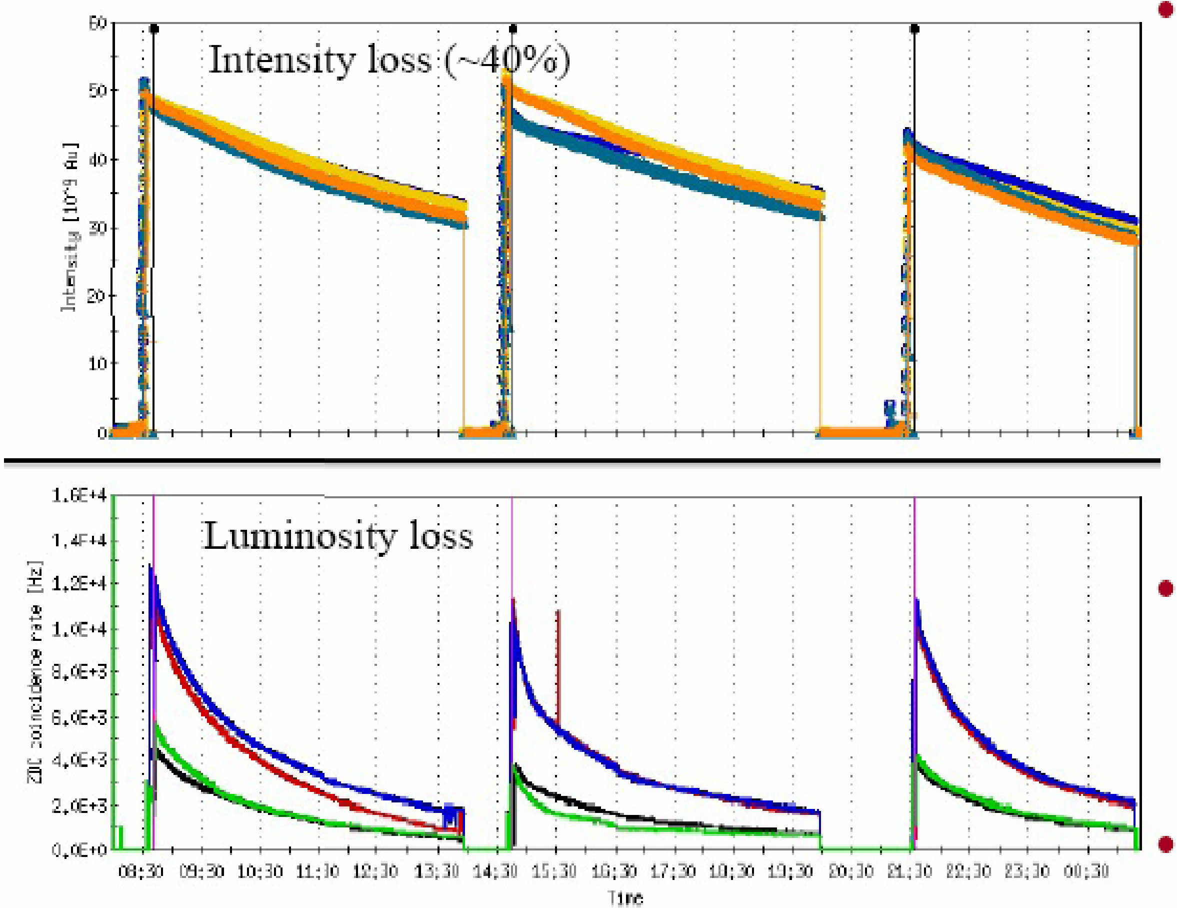


This is our Task.

M. Bai

Au-Au Luminosity limit: intra-beam scattering

J. Wei. ICFA Workshop, October 18, 2004

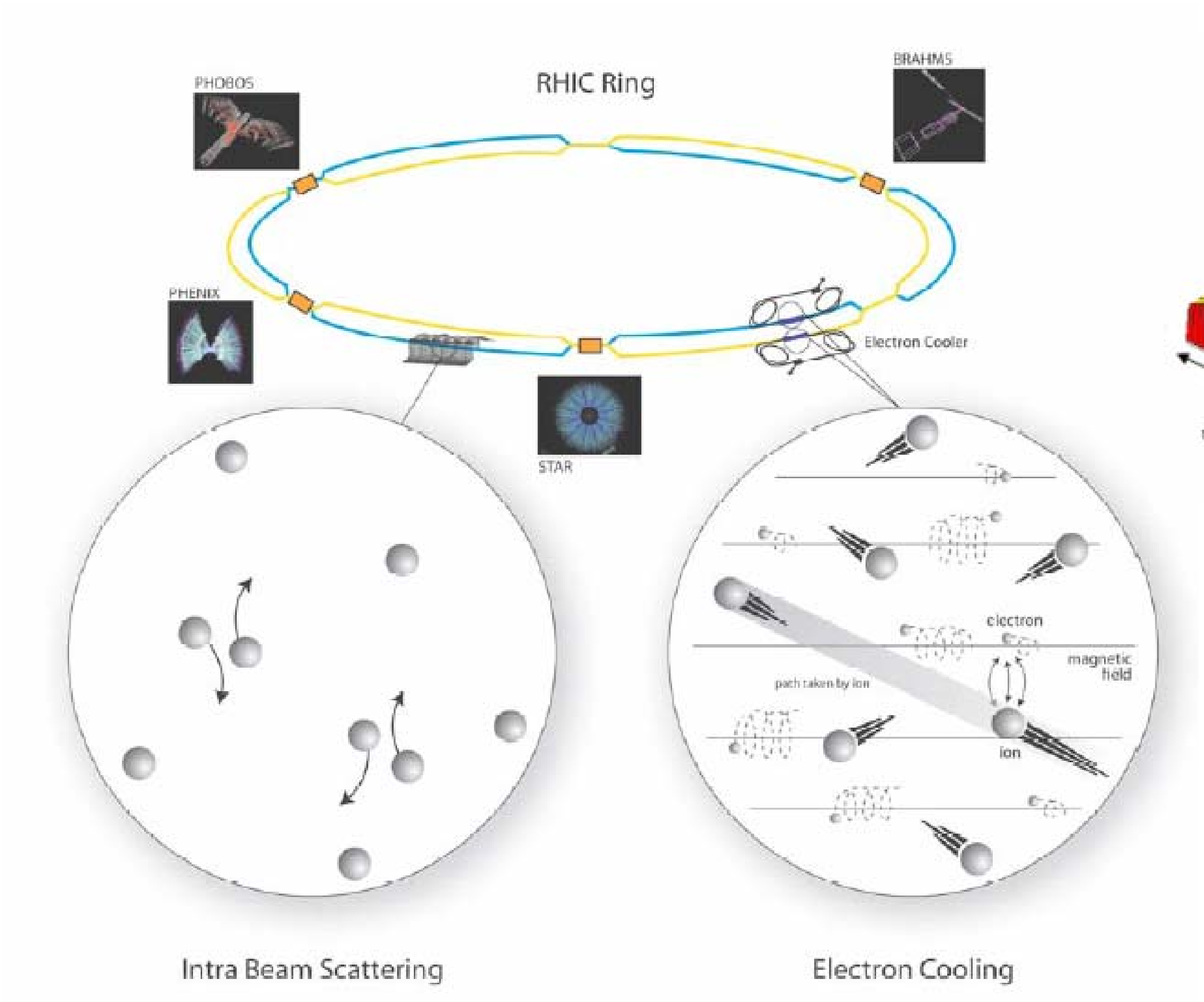


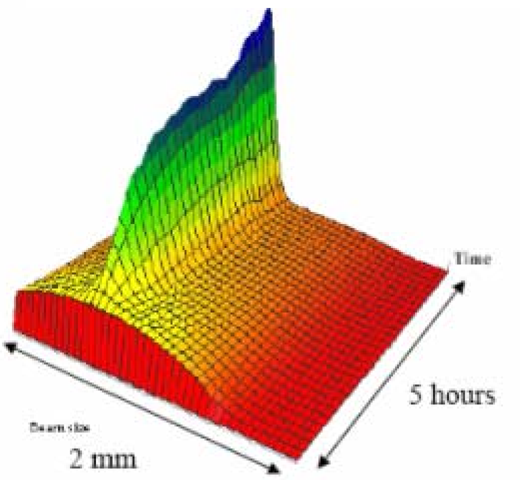
Time (~5 hour per fill)

- Luminosity loss – frequent refill
  - Transverse emittance growth
  - Longitudinal growth & beam loss due to RF voltage limitation
- De-bunching & physics background – beam gap cleaning
- IBS: Z^4/A^2 scaling

RHIC II

I. Ben-Zvi *et al*. ZDR Electron Cooling for RHIC, 2004

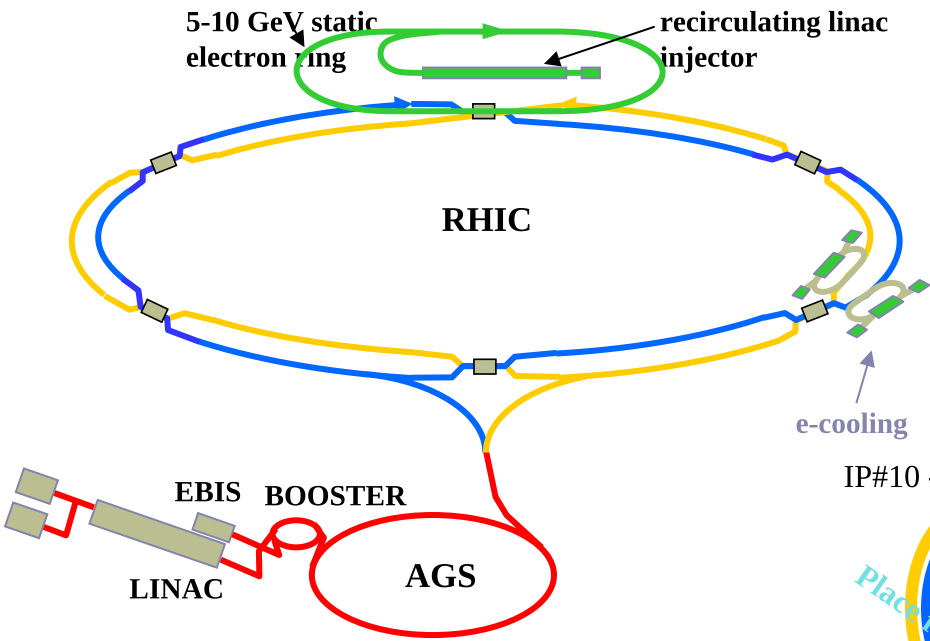




A. Fedotov

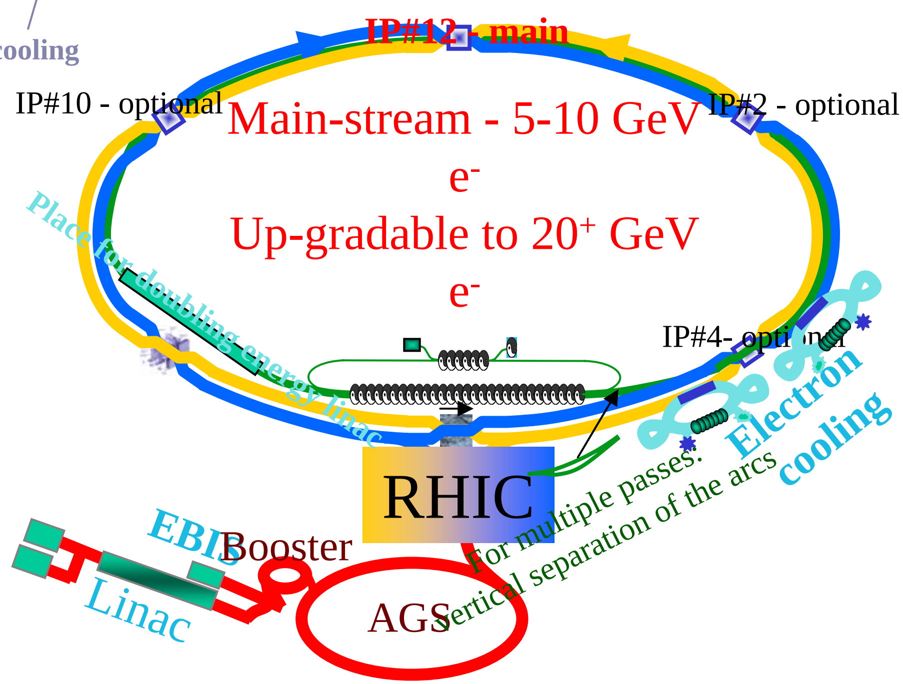
Electron-Ion Collider at RHIC: eRHIC

V. Ptitsyn *et al*. eRHIC ZDR, 2004



Linac-ring option

I. Ben-Zvi, V.Litvinenko *et al*.

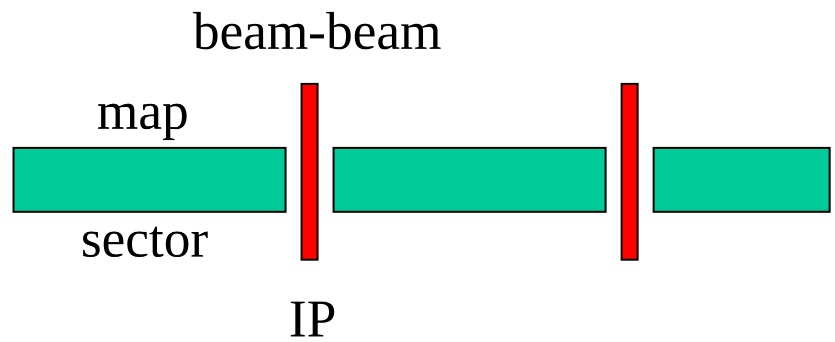


10 GeV, 0.5 A e-ring with 1/3 of the RHIC circumference (similar to PEP II HER)

Conceptual Model of the Beam-Beam Application

Core Part:

1. Sector map
2. Beam-beam kick

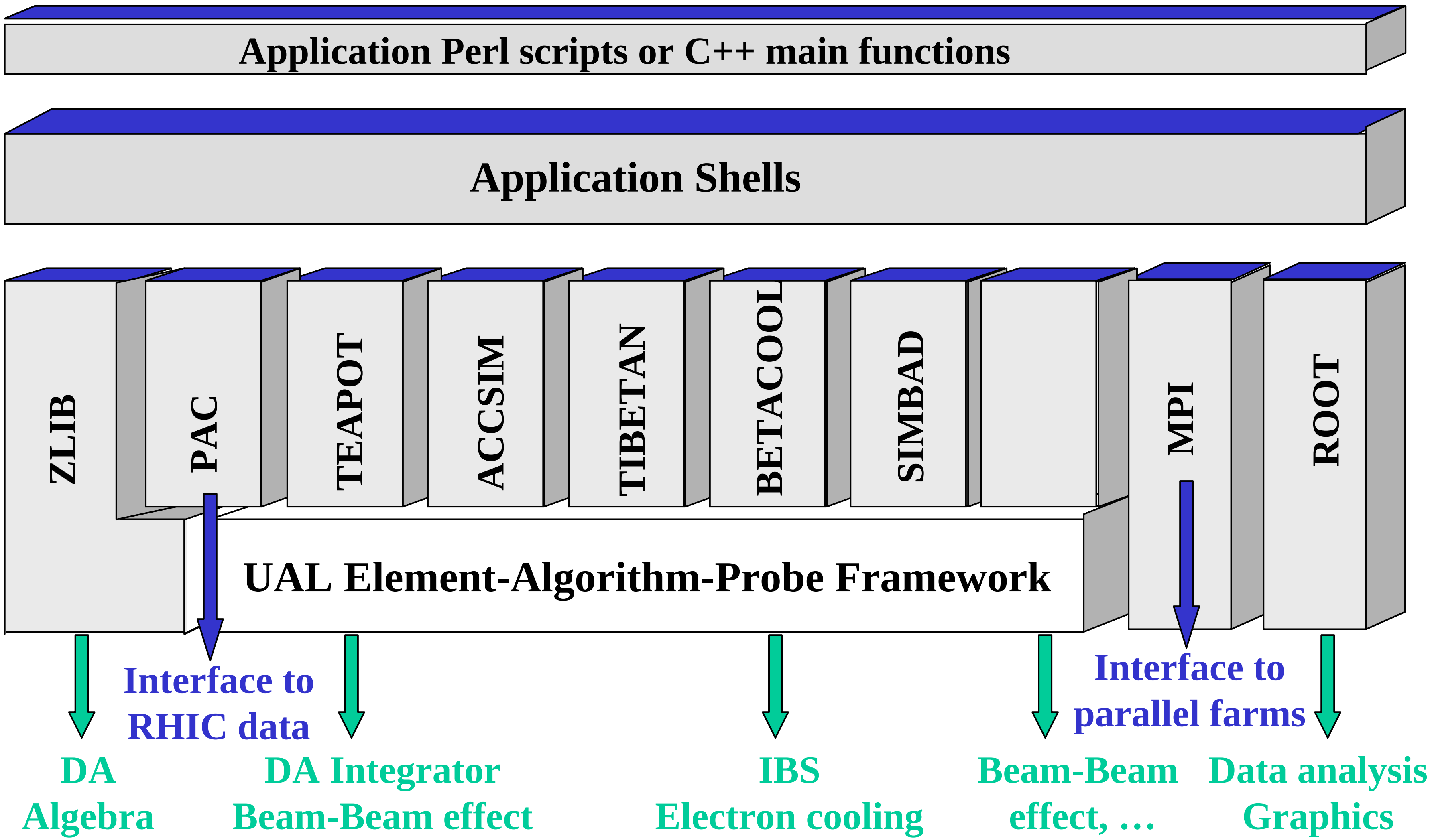


Unidentified Feasible Objects (UFO) :

- tune modulation
- beam-beam offsets
- intra-beam scattering
- electron cooling
- …

Unified Accelerator Libraries (UAL) Environment

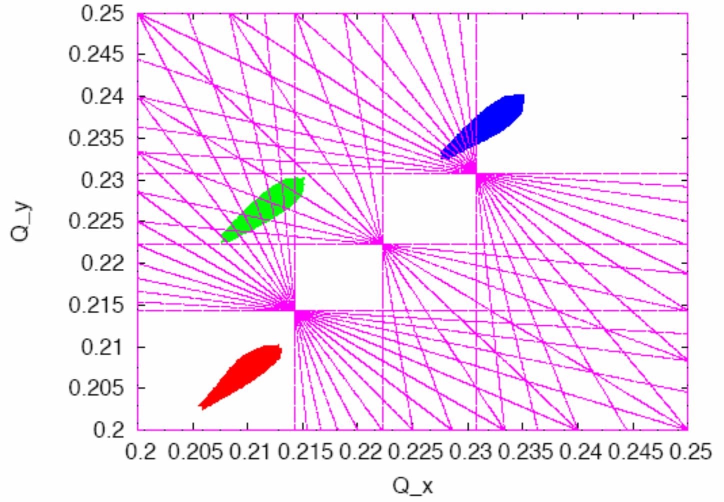
http://www.ual.bnl.gov

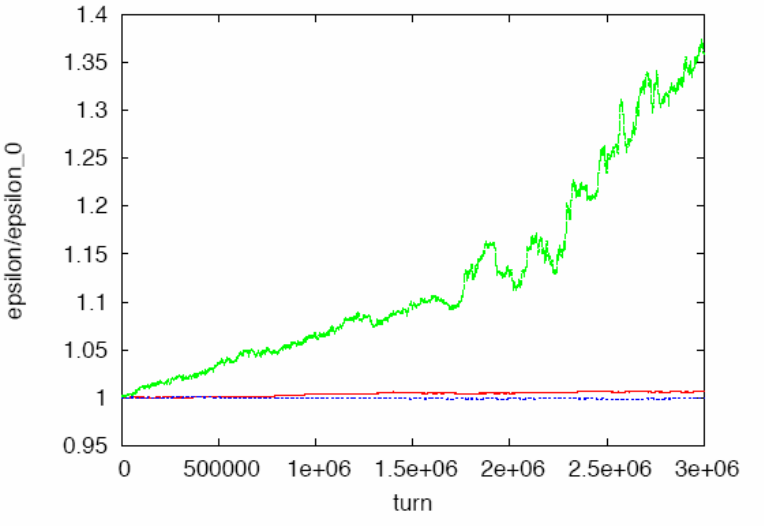


RHIC II basic beam-beam modeling with the bi-Gaussian beam (C. Montag)

Basic Model :

- Linear matrix + chromatic effects
- Beam-beam kick
- Random tune fluctuation





Beam-Beam Effect

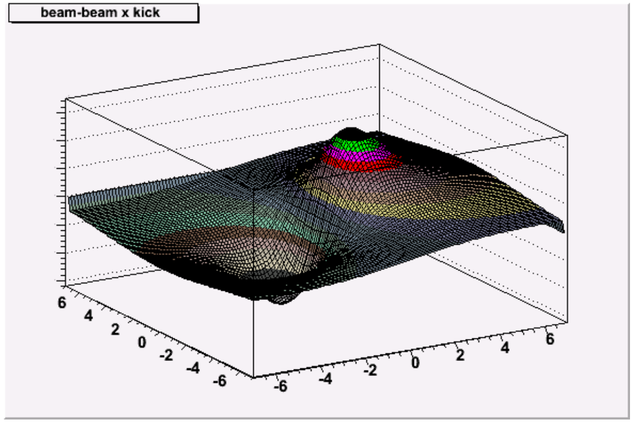
Electric Field Due to Gaussian Distribution:

Basseti and Erskine, CERN-ISR-TH/80-06

$$\begin{pmatrix} E_x \\ E_y \end{pmatrix} = \frac{\lambda}{2\epsilon_0\sqrt{\pi}} \frac{1}{s} \begin{pmatrix} \Im \\ \Re \end{pmatrix} \left(w\left(\frac{x_w}{s} + i\,\frac{y_w}{s}\right) - e^{-\left(\frac{x_w^2}{2s_x^2} + \frac{y_w^2}{2s_y^2}\right)} w\left(\frac{x_w}{s}\frac{s_y}{s_x} + i\,\frac{y_w}{s}\frac{s_x}{s_y}\right)\right)$$

Electric Field of the Round Gaussian Beam:

$$\begin{pmatrix} E_x \\ E_y \end{pmatrix} = \frac{\lambda}{2\pi\epsilon_0} \frac{1 - e^{-r^2/(2s^2)}}{r^2} \begin{pmatrix} x \\ y \end{pmatrix}$$



Other approaches:

1. Y.Okamoto, R.Talman. Rational Approximation of the Complex Error Function.
2. J. Qiang, M.Furman, R.Ryne. Strong-Strong Particle-In-Cell approach.
3. K. Ohmi. Quasi-Strong-Strong algorithm.
4. W.Herr, M.P.Zorzano, F.Jones. Hybrid fast multipole method.

…

Sector Map

1. **Linear Matrix:**

   $x_i = M_{ij}\, x_j$, where i,j = 1,..6

   codes: a few lines

   - **fast**
   - **no non-linear effects**

2. **Taylor Map**

   $x_i = M_{ij}\, x_j + T_{ijk}\, x_j x_k + \ldots$

   codes: UAL/ZLIB, PTC, …

   - **does include non-linear effects**
   - **faster then element-by-element tracking**
   - **not symplectic**

3. **Dragt-Finn Factorization**

   $M = R\exp(:f_3:)\exp(:f_4:) \ldots \exp(:f_{\Omega+1}:)$

   $$\exp(:f:) = \sum \frac{1}{m!}[f,]^m$$

   codes: MARYLIE, PTC, COSY INFINITY, …

   - **symplectic (in theory)**
   - **computation is based on Taylor series**

4. **Irwin's kick factorization**

   $M = R{*}M_1{*}\exp(:g_1:)M_1^{-1}M_2\exp(:g_2:)\ldots$

   $\exp(:g:) = 1 + [g,]$

   - **includes non-linear effects**
   - **computation is based on linear matrices and symplectic non-liner kicks**

Computational time of various algorithms running on the 2.4 GHz CPU

Model Components	Time, μs
RHIC (revolution period)	12.5
Basic model:	
The uncoupled linear matrix with chromatic effects	0.35
The round beam-beam kick	0.7
DA-based mappers:	
1st order (linear) Taylor map	4
5th order (decapole, dodecapole) Taylor map	45
Irwin's kick factorization (Γ – number of kicks and linear matrices)	
3rd order, $\Gamma = 12$	2.4+
5th order, $\Gamma = 27$	5.4+

Timing Budget of the proposed beam-beam application

Single-particle one-turn tracking:

- Weak-strong round beam-beam kick: 4*0.7 μs
- Irwin's 3rd order kick factorization: 4*2.4 μs

12.4 μs

Multi-particle multi-turn application:

1K particles *100M turns *12.4 μs = 344 hours

Parallel version is embarrassingly scalable because it can be divided into a sequence of steps containing one beam-beam force calculation per several thousand turns of serial tracking

Practical calculation time: 8 hours

Required computer resources: 344/8 = 43 CPUs

Benchmark results

	Time, μs	
	ZLIB linear mapping	MPI_Allreduce integer
Desktop, 2.4 GHz	4	-
CDIC Linux cluster		
4 CPUs	4.4	1300
32 CPUs	5.4	1500
IBM BlueGene/L		
32 CPUs	19.6	3.4
128 CPUs	19.7	4.6
512 CPUs	19.8	5.2

Brief summary of BG/L :

1. Communication is extremely fast *(mapping vs MPI_Allreduce)* and weakly depends on the number of nodes
2. System is very homogeneous *(mapping time is constant)*
3. Each CPU is 4-5 times slower then CDIC one, but a complex with 1000 CPUs will bring an additional performance factor of 8.

Summary

- Beam-beam effect is a major limiting factor for luminosity of the present RHIC proton operations and future RHIC II and eRHIC facilities.
- So far, there is no comprehensive model explaining the RHIC beam-beam tune spread criteria (ξ = 0.015-0.020)
- UAL off-line simulation environment addresses this task by providing a mechanism for composing such a model from an open collection of various tracking algorithms and physical effects.
- CDIC Linux cluster meets the immediate requirements of the initial beam-beam applications
- IBM BlueGene/L may bring the additional performance factor, opening a door for advanced algorithms (e.g. higher order maps, PIC approach, *etc.*) and/or additional effects (e.g. ibs, electron cooling, *etc*.)